Volume I

Report
on
High Energy Solar Spectroscopic Imager (HESSI) Test Mishap

By the
HESSI Test
Mishap Investigation Board

Released May 18, 2000

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Volume II

Volume II contains the supporting data Appendices for the diagnostics and analyses that were conducted during the investigation. Included are all of the supporting data, diagrams, and figures referenced in Volume I as well as a complete set of response data from the sine and random testing of HESSI.

1. ACKNOWLEDGMENTS

The HESSI Test Mishap Investigation Board (MIB) wishes to thank:

- the vibration test and support personnel at the Jet Propulsion Laboratory (JPL),
- the software support personnel from m+p international GmbH (m+p),
- the HESSI spacecraft personnel from Spectrum Astro, and
- the HESSI spacecraft personnel from University of California at Berkeley (UCB)

for their cooperation, support, and technical analyses which were crucial to the resolution of the HESSI Test mishap.

The cooperation and responsiveness the Board received during the investigations at Jet Propulsion Laboratory from the many individuals involved with the HESSI spacecraft testing are to be highly commended. It was obvious to the Board that the JPL Environmental Test Laboratory personnel are very conscientious and were highly motivated toward assisting us in determining the cause of the mishap.

In addition, the MIB Chair thanks the Board members and Board support personnel. It is indeed a pleasure and honor to lead such a group of highly motivated and technically excellent personnel. The MIB Chair gives special recognition to Mr. Rodney Phillips, MIB member. Rodney personally coordinated, integrated and led the detail technical aspects of this report. His technical excellence, dedication and long hours spent on this report are appreciated. A special thanks to Mrs. Jackie Sneed, who developed this manuscript. The entire Board appreciates her patience, dedication, hard work and long hours.

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4. EXECUTIVE SUMMARY

The High Energy Spectroscopic Imager (HESSI) spacecraft primary mission objective is to explore the basic physics of particle acceleration and explosive energy release in solar flares. The HESSI spacecraft was scheduled for a July, 2000, launch on a Pegasus vehicle as part of the Small Explorer Program (SMEX). On March 21, 2000, the HESSI spacecraft was being subjected to a series of vibration tests at JPL as a part of its flight certification program. The structural qualification test, denoted as the sine-burst test, subjected the spacecraft to a major overtest that resulted in significant structural damage to the spacecraft. The incident has been designated as a Class A mishap since the damage exceeded $1 million.

Vibration testing of the spacecraft certifies the flight hardware to the environmental loading conditions experienced during the ground, captive carry and flight mission phases. Dynamic testing for a Pegasus air-launched SMEX payload is governed by section 4 of the Pegasus User's Guide (reference Appendix I-1). Three types of vibration tests were designated for HESSI. A low-amplitude sine survey, not a qualification test, is done to assess the fidelity of the analytical model and to identify the major structural resonances of the spacecraft. A random qualification test is done to account for the high-frequency effects of acoustically induced vibrations that occur during captive carry, launch and flight. The third test is a sine-burst that is done to qualify the spacecraft for structural integrity. In the sine-burst test, quasi-static loading is applied to the structure via an electrodynamic exciter (shaker) in lieu of a static pull or a centrifuge test.

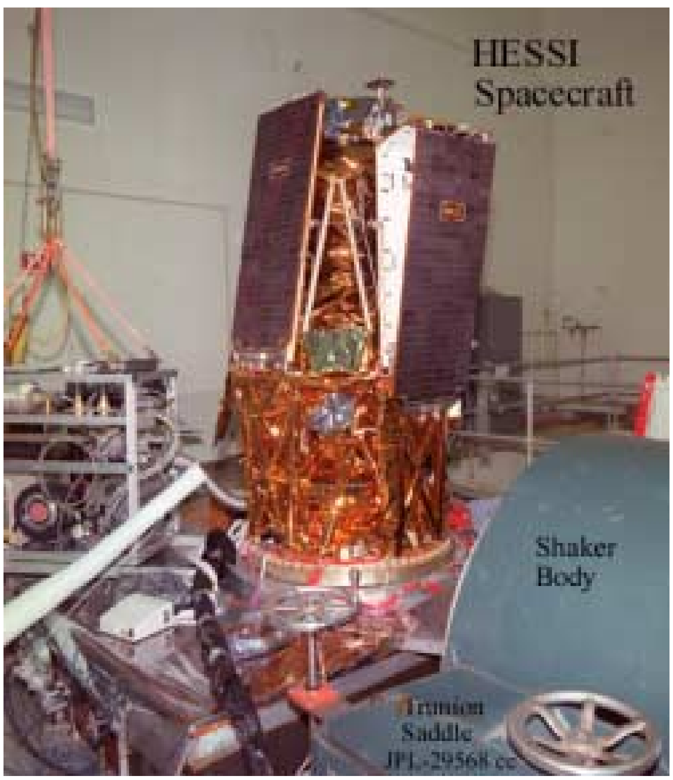

Figure 4-1

The HESSI MIB developed a detailed fault tree and used test and analysis data to address each probable cause of the overtest. We then developed diagnostic test plans that allowed us to attempt to replicate the overtest condition. We were able to achieve a sine-burst amplitude overshoot during our diagnostic testing that validated our hypothesis about the cause and mechanism of the overtest. As a result, the MIB determined that the sine-burst overtest was caused by a poor estimate by the vibration control system of the overall gain characteristics of the shaker system. The accuracy of the gain estimate was compromised by the existence of intense static friction (stiction) between the granite reaction mass and the shaker system slip plate and a pretest self-check performed at force input levels that were too low to overcome the stiction in the system. The self-check is a short duration, pseudo-random noise signal that the controller uses as a known quantity. It emits the signal through the shaker system and characterizes the response of the system based on the resulting acceleration profile of the slip table. Therefore, when the pretest self-check was performed at very low amplitude, the control system sensed a high resistive force due to the stiction and, consequently, calculated a very high forcing function. This high, calculated forcing function was more than sufficient to overcome the stiction in the system and resulted in a large overshoot of the desired sine-burst amplitude. A higher self-check would have lessened the effect of the stiction on the system characterization, but would not have eliminated it.

The root cause of the overtest condition was the stiction between the slip table and the granite mass. It resulted from physical contact between a portion of the slip table and the granite mass caused by a mechanical failure in the shaker's support structure. The stiction caused the shaker system to present highly non-linear gain characteristics to the control system making it impossible for the controller to calculate an appropriate forcing function.

Data were available from the control system in the form of the calculated system transfer function from the self-check of the ill-fated sine-burst test that indicated stiction in the shaker system. A contributing factor to the incident was the lack of a procedural requirement for the test operator to evaluate this critical system response data before proceeding to the actual test. Failure to perform a representative facility validation test for sine-burst before mounting the HESSI spacecraft was an additional contributing factor to the mishap. A sine-burst validation test would have shown the stiction in the shaker system and would have allowed the JPL personnel to correct its cause before mounting the spacecraft.

Having ascertained the exact cause and nature of the test mishap, the Board prepared a list of corrective actions that would mitigate the possibility of a similar test mishap. These actions were presented to JPL as conditions for their resumption of vibration testing activities (reference Appendix I-2). Additionally, a corrective action plan was presented to JPL that, upon its completion, will allow JPL to resume vibration testing on the affected Ling A-249 shaker (reference Appendix I-3). One of the conditions imposed was that the shaker be refurbished or replaced. We identified a shaker, another Ling A-249, that was being excessed from MSFC. We were able to reclaim the shaker from excess property and have it shipped to JPL to furnish them with the necessary components for the refurbishment of their A-249. The shaker from MSFC is actually a newer serial number than the damaged one and incorporates a better design in the trunion saddle mounting system that should prove to be more robust.

5. BOARD ORGANIZATION, METHOD OF INVESTIGATION

Board Organization

The HESSI spacecraft, designed to acquire images and spectroscopy during the solar maximum and planned for launch in July 2000, was severely damaged during a vibration test at the Jet Propulsion Laboratory (JPL), in Pasadena, California, on March 21, 2000.

The HESSI Test MIB was formed on March 24, 2000 in response to the NASA Headquarters, Associate Administrator for Space Science request. The damage was designated as a Class A mishap. Board membership included experts from NASA HQ, GSFC, KSC, MSFC and the University of California at Berkeley (UCB). The Board activities were conducted in accordance with the provisions of NPD 8621.1G (reference Appendix I-4) and NPG 8621.1 (Draft).

The MIB was established in the public's interest to address the following points:

1. Determine the root cause of the vibration-testing anomaly on HESSI.
2. Provide an analysis of why the established processes failed.
3. Identify steps that should be taken to strengthen or augment established processes to prevent similar occurrences in the future.

At the first MIB meeting on March 24, the individual team members quickly blended to form an integrated team fostering full and open communications.

The MIB meetings were conducted at JPL on March 24 – 30, 2000. Additional meetings were held at GSFC on April 10 – 12, and at NASA Headquarters on May 3 and 4, 2000. Regular telecons were also conducted with the Board and technical teams through April and May.

Method of Investigation

A fault tree (reference Appendix H-1) was used for a structured analysis of the possible causes that might have resulted in this overtest. The basis for the fault tree came largely from the experience base of the Board members and historical precedent. Data were provided by the facility operating personnel that would support or refute portions of the fault tree. Structured interviews of the personnel involved were also utilized as data to support or eliminate fault tree possibilities. As the fault tree was narrowed to specific areas of concern, diagnostic test plans were generated and executed in an attempt to reproduce the set of conditions that resulted in the overtest in question.

6. NARRATIVE DESCRIPTION OF MISHAP

Test Overview

The HESSI spacecraft was mounted to an adapter ring that was then mounted to the magnesium alloy slip table via an aluminum fixture plate, as shown in Figure 6-1, in preparation for testing in the spacecraft's X direction. Twenty-four force gages were placed between the spacecraft adapter ring and the fixture plate at each of the attachment bolt locations to measure the force input to the spacecraft.

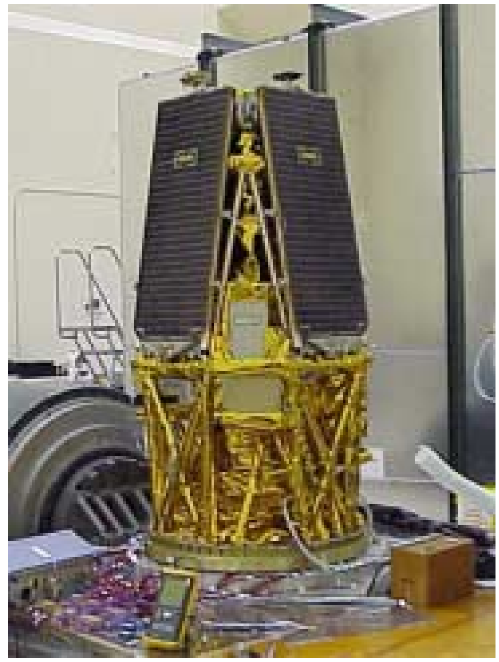

Figure 6-1

A Ling A-249 shaker, rotated to a horizontal configuration, was attached to the slip table to provide lateral excitation. The shaker and granite mass, located in Building 144 room 100, are mounted directly to an isolated floor section. The weights of the spacecraft, slip table, fixtures, and attachments are shown in Appendix J-1.

Two Endevco Model 2271A/AM20 accelerometers were mounted on the fixture plate in the axis of excitation and provided the control system acceleration feedback data for closed loop shaker control during swept sine and random vibration testing. Only one of these accelerometers was used for shaker control during sine-burst vibration testing.

A Trig-Tek Model 1273A Charge Amplifier provided signal conditioning of the control accelerometers. An m+p VCP9000 Vibration Control System processed the conditioned control acceleration data for update of the exciter drive signal based on system characteristics measured during the vibration tests.

The controller and associated equipment was located in room 104 adjacent to the test area. A photograph of the controller and some of the associated equipment is shown in Appendix K, photo K-1. For a detailed description of how a vibration test is controlled, a list of equipment, and block diagrams of how it is connected, reference Appendix J-2.

A separate instrumentation system is used to record the responses of the spacecraft accelerometers and force transducers. The twenty-four Kistler Model 9251A force gages were summed together and conditioned using a Kistler Model 5017B(X) charge amplifier. An Endevco ICAS, model 2735 or model 2775A charge amplifier provided conditioning for the fifty-eight response accelerometers. Two Metrum digital tape recorders archived the conditioned force gage and response acceleration data for post-test data retrieval.

One of the Metrums recorded an independent monitor accelerometer, mounted next to the control accelerometer that was used to measure the input acceleration independently. The Metrum also recorded the two control accelerometer signals from the tape output of the Trig-Tek charge amplifier located in the control room. Some of the response channels were also acquired and processed by the m+p Vibration Control System to be used as limit channels during random vibration or for quick-look response data.

All of the instrumentation system equipment is located down the hall from the control room, in room 113. Details of the equipment used and calibration data are in Appendix I-26. A photograph of some of the instrumentation equipment used for the HESSI test series is shown in Appendix K, photo K-2.

Timeline Summary

On the evening of March 21st, as the last major test of the series before rotating the spacecraft to the other lateral axis, a sine-burst test was performed on the HESSI spacecraft in flight configuration. A sequence of six –12dB (1/4 of full level) sine-bursts was to be performed followed by a single –6dB (1/2 of full level) and a single full level after review of the input and some responses. On the initial –12dB burst, an overtest of 21g's was performed, damaging the HESSI spacecraft solar arrays and structure.

March 8, 2000 – The Ling A-249 is rolled down to the horizontal position for a scheduled MARS 01 Robotic Arm vibration test. The shaker bullnose is attached to the slip-plate and all mounting bolts are torqued. The shaker/slip-plate is aligned to the hydrostatic bearing by leaving the bearing mounting bolts loose and stroking the shaker/slip-plate at a low frequency and high displacement. This allows the bearing to align itself. The mounting bolts are then tightened while observing the time history of the control accelerometer that is mounted on the slip-plate. Nothing unusual is noted. The Robotic Arm vibration test is completed on March 10, 2000. No anomalies are noted.

March 13, 2000 – HESSI Accelerometer and Thermocouple locations are defined. Thermocouples are installed in the afternoon and evening.

March 14, 2000 – HESSI accelerometers are installed. Thermal blanketing begins.

March 16, 2000 - A low level, (+/-) 0.25g, sinusoidal frequency sweep is performed to verify the shaker setup prior to installing the HESSI spacecraft. The frequency is swept from 5-2000Hz at 2 octaves/minute – nothing unusual is noted.

March 17, 2000 – The twenty-four triaxial force gages are installed, aligned and interconnected.

March 20, 2000 – HESSI is mounted to the slip table late in the afternoon. Accelerometers are connected to the signal conditioning and tested.

March 21, 2000 – The morning is spent preloading the interface bolts and finishing up instrumentation checkout and verification. Testing begins after lunch.

13:18 – Run #1 is conducted: a 0.25g sine survey 10-2000Hz at 4 octaves/minute. Channel 26 overloads causing an abort at 41.19Hz.

13:39 – Run #2 is a successful repeat of run #1.

14:14 – Run #3 is conducted: a -18 dB random for 30 seconds without force limiting.

14:54 – Run #4 is conducted: a -12 dB random for 30 seconds with force limiting.

16:03 – Run #5 is conducted: a -6 dB random for 30 seconds with force limiting and response limiting on channels 23, 24, 25, 26, and 47. Test aborts after 24 seconds due to overload on channel 26.

16:45 – Run #6 is conducted: a full level random with force limiting and response limiting on channels 23, 24, 25, and 47 at 0.5g^2/Hz. Test aborts after 1 second due to overload.

17:04 – Run #7 is conducted: a full level random with force limiting and response limiting on channels 23, 24, 25, and 47. Test aborts after 2 seconds due to overload on channel 25.

17:16 – Run #8 is conducted: a full level random with force limiting and response limiting on channels 23, 24, and 47. Test aborts after 2 seconds due to overload on channel 47.

17:50 – Run #9 is conducted: a full level random with force limiting and hard notches instead of response limiting. Test runs successfully.

18:13 – Run #10 is conducted: a 0.25g sine survey 10-2000Hz at 4 octaves/minute. Comparison with run #2 reveals that spacecraft modes have not changed.

18:43 – Run #11 is conducted: a single pulse intended to be –12 dB level (1.88g's peak) results in an overtest and damage to the spacecraft. Test is aborted manually. Pumps, amplifier, and controller are secured. No faults are indicated by the controller or amplifier.

18:45 – Orderly electrical shutdown of spacecraft is performed.

18:46 – The flight battery plug is removed from the spacecraft.

18:47 – The damaged solar arrays are supported with harness lacing cord to prevent injury or further damage to the spacecraft.

18:48 – Visual inspection begins for other unsafe conditions and structural damage.

18:53 – Several adapter plate mounting bolts are checked and found to be loose.

19:03 – The vacuum pump is positioned and connected to the Cyrostat.

Also that evening, the facility supervisor is called at home and the test cell is secured.

March 22, 2000 – at 06:00 one of the facility operators turned on some of the equipment and reconfigured for calibration. After checking voice mail and hearing a message that nothing should be disturbed, the operator restored the equipment and configuration back to its original state. The HESSI crew returned later in the morning and performed additional non-invasive visual inspections. In the afternoon a security guard was in place and access was restricted to the test cell.

7. FAULT TREE SUMMARY ANALYSIS

The fault tree, shown in Appendix H-1, was used for a structured analysis of the possible causes of the overtest mishap. The probable causes are numbered in a logical hierarchical manner with the highest levels being Facility Failure (A1) or Spacecraft Anomaly (A2).

Each branch, with its associated causes, was analyzed and data were used to support or refute it. The critical mishap path was Facility Failure (A1), due to Performance Error (A11), caused by Slip Table Stiction (A111) created by Table to Granite Misalignment (A1111) due to Shaker Position Shift (A1111B). The detail analysis is covered in this section.

FACILITY FAILURE (A1)

Performance Error (A11)

Slip Table Stiction (A111)

Increased frictional drag in a shaker system causes the moving elements of the system to exhibit a greater than normal coefficient of static friction, or a condition known as stiction. Although this condition will also result in increased drag under dynamic conditions, its effects are greatest when two bodies are at rest. We conclude from the supporting data and the personal interviews that a stiction condition was present throughout the day’s testing on March 21. Time history plots (reference Appendix I-5) reveal stiction during the 0.25g sine sweep of run 10. The glitches in the acceleration plot that occur immediately after the zero velocity points are indicative of stiction in a system. The acceleration glitches have large amplitudes and show very sharp drop-off rates indicating severe stiction in the system. Interviews of the JPL test operations personnel indicate the condition affected the random equalization as well. Both operators stated that when the exciter control system would begin its equalization process during the low-level random tests the low-frequency spectral content was initially higher than anticipated. This low-frequency anomaly during the initial equalization loops of the random tests resulted from poor system transfer function estimates brought on by stiction in the shaker system. Other test observers stated in interviews that they sensed the low-level random tests were loud at first with decreasing volume as the equalization process progressed for the particular test level. This observation corroborates the visual observation of the test operators. The response of the exciter system will be most affected by stiction in the lower-frequency regime where displacements are relatively large. A review of the control accelerometer PSD from the self-check of run 11, (reference Appendix I-6D) shows the response of the system was poor in the low-frequency region, actually reaching a minimum at 30Hz.

Potential causes of stiction in a slip table can be insufficient or absence of oil flow, contaminated oil, table warpage, or a mechanical alignment anomaly. The possibility that the stiction was caused by either insufficient or no oil flow, contaminated oil, or table warpage or a combination of these maladies was systematically eliminated from consideration. The detailed rationale for the elimination of these possibilities is contained in Appendix H, Section (A111).

Table to Granite Misalignment (A1111)

The investigation into alignment anomalies focused on the granite mass, the magnesium alloy slip table that rides above it, and the Ling A-249 shaker (reference J-6). Stiction in a shaker system is often the result of some misalignment between two or more of the moving components in the system. These systems require precise alignment to function properly. This shaker system at JPL is used for both horizontal and vertical testing. The shaker must be repositioned from the vertical to the horizontal configuration for each 3-axis test series. Each repositioning of the shaker requires realignment of the slip table system. After the system is aligned, any shift in relative position of any of the major components can result in excessive frictional drag in the system. This drag can result in a stiction condition that is consistent with our data analysis. It is particularly critical that the granite mass and the slip table be in parallel planes and that the gap between them be consistent across the area of the slip table for the oil film type table to function properly. An interview with the JPL test person that configured the system for this test indicated that the system was aligned and functioning properly after it was configured for horizontal operation. As a part of our diagnostic testing we performed a series of measurements to quantify the gap distances between the slip table and the granite mass at various locations. These measurements are shown in Appendix J-3. A review of these measurements show that the slip table and granite are not parallel and are actually in contact with each other at one location. This condition is consistent with the type of anomaly that we suspected as the cause of the stiction condition noted above.

Granite Mass Position Shift (A1111A):

One of the causes of a slip table to granite mass misalignment would be a shift in position of the granite mass. We performed a visual inspection of both the slip table and granite mass as part of our diagnostic testing. The granite mass did not appear to have shifted.

Shaker Position Shift (A1111B):

The other cause of the slip table to granite mass misalignment would be a shift in the position of the shaker. A visual inspection of the shaker indicated that the shaker may have shifted on its mounting base. The north side mounting saddle was obviously sitting at an angle from vertical and two of the 1” diameter, grade 8 bolts that secure the saddles down to the base were obviously bent. Further visual inspection from the rear of the shaker revealed that the shaker is rotated slightly clockwise about its center axis and that the north side trunion position is low. This anomaly accounts for the table to granite gap measurements referenced. The slip table is affixed to the shaker armature by a piece of interface hardware known in the industry as a bullnose. The bullnose provides a very rigid attachment to the shaker armature. The shaker armature itself has both linear bearings and flexures, as detailed in Appendix H, Sections (A1121A) and (A1121B), that function to maintain its position and provide for uniaxial motion. The armature support and bullnose are rigid enough to translate the shaker shift into the table misalignment noted above. We determined from our inspection that the shaker position shift was the cause of the slip table and granite mass misalignment that generated the stiction in the system that led to the overtest.

Analysis of the time-history of the control accelerometer from run 11 (reference Appendix I-7a) shows an interesting characteristic. The pulse ramps up normally from zero and reaches an amplitude plateau at approximately 21gpk for almost 5 full cycles before ramping back down to zero. Analysis of the target pulse (reference Appendix I-8) shows that the desired waveform ramps up from zero to its maximum amplitude, stays at maximum for only one full cycle and ramps back down to zero. The discrepancy in the waveforms is easily explained. At first glance one might interpret the test data as being electrically clipped, however, it is not clipped. We know from the as-run test setup sheet, (reference Appendix I-22), that channel 1 (the control accelerometer) for the controller is set for 100mV/g. We see also from the as-run test procedure (reference Appendix C-3 procedure page 13) that the charge amplifier full-scale was set for 100g. With a 21g pulse there would be no danger of clipping the control channel. The shaker body provides the reaction mass that the armature force pushes against. The Ling A-249 has a rubber isolation system that is intended to lessen the transmitted vibration from the body of the shaker to the floor when the shaker is in the vertical configuration. If this isolation system is not mechanically locked out when the shaker is changed to the horizontal configuration, it will allow the shaker body to move if sufficient force is applied. The isolation system basically consists of layers or ribbed rubber pads that reside between the trunion saddle and the shaker base. These pads are in shear during horizontal operation and have the considerable weight of the shaker body, in excess of 20,000 lbs, resting on them. When the drive signal of the computer ramped up to sufficient amplitude such that the force in the system, approximately 45,000 lbf, overcame the shear force resistance in the shaker isolation system the shaker body began to move. The body continued to react until the force ramped back down to that same amplitude at which time the shaker body ceased to move. Close examination of the time histories of the control accelerometer (reference Appendix I-7a) and the force sum-X for the spacecraft (reference Appendix 7b) shows that when the spacecraft mounting interface began to slip (i.e., when the force indication began to decrease) the acceleration peak actually rose slightly from 20g to 21.5g. This indicates that the reactive motion of the shaker body was slightly reduced yielding a slight increase in the measured acceleration at the fixture plate. This reaction of the body accounts for the amplitude plateau in the acceleration time-history. The reactive motion of the shaker body actually acted to lessen the damage that could have occurred to the spacecraft. If the isolation system had been locked out, the shaker system would have continued to follow the amplitude ramp up until the amplifier or shaker reached a hard limit or the computer drive signal ramped back down. We recognize that the movement of the shaker body quite possibly exacerbated the misalignment conditions noted, however, it is evident that its movement did not cause the trunion condition.

Subsequent disassembly of the shaker system by the JPL laboratory personnel revealed that the trunion support needle bearing on the north side of the shaker has a broken outer race and some of the rollers are loose and missing from the bearing housing. The 1”, grade 8 bolts mentioned above are actually broken with the through holes for the fasteners being misaligned with the threaded holes by approximately ½ diameter of the fastener. The underside of the slip table is also damaged. The area of contact between the slip table and the granite mass generated sufficient heat due to friction to cause the magnesium alloy material from the plate to deposit onto the granite mass, refer to Figure 7-1 below. The plate has an area of material loss that is consistent with the metallic deposit found on the granite mass, refer to Figure 7-2 below. The damage to the bottom of the slip table is not consistent with a shock event that has duration of only a few cycles. It is consistent with several minutes of operation during which heat would have continued to build in that local contact area. The slip table and granite would have to operate in a “rubbing” condition for sufficient time to build enough heat in that area to cause the deposit of the magnesium alloy onto the granite mass. It is evident that the material loss of the damaged area of the slip table is not simply the result of abrasion. Ample evidence has been detailed that shows the stiction condition was present throughout the day’s testing.

Figure 7-1

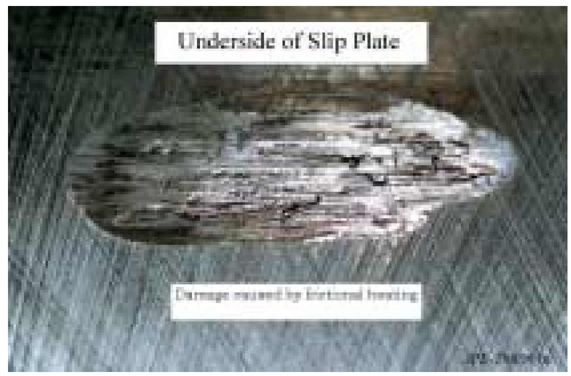

Figure 7-2

Shaker Performance Error (A112)

Shaker system faults can cause test anomalies in several ways. Broken flexures or damaged bearings can lead to stiction in the system. An intermittent field coil can cause a pronounced system gain anomaly that will lead to a test overshoot. There are also other mechanical and electrical failures that can lead to testing anomalies. Each of these possibilities was investigated as a possible cause and supporting data were used to systematically eliminate them as a probable cause. The rationale for their elimination as contributing factors to the event is detailed in Appendix H, Section (A112) in the Fault Tree analysis.

Amplifier Performance Error (A113)

There are some power amplifier failures that will generate overtest conditions. Supply power faults and other electrical failures can send catastrophic transients through the shaker system. The amplifier can also exhibit non-linear gain characteristics that can cause a test overshoot. Each of these possibilities was investigated as a possible cause and supporting data were used to systematically eliminate them as a probable cause. The rationale for their elimination as contributing factors to the event is detailed in Appendix H, Section (A113) in the Fault Tree analysis.

<u>Controller Output is Incorrect (A12)</u>

An incorrect drive signal could have been caused by an incorrect controller output signal sent to the amplifier. This could be caused by a software error, setup error, Digital to

Analog Converter (DAC) fault, power fault, procedure error, or too low of a self-check. Of these, the only possible error was too low of a self-check signal. The self-check selected for this test works under normal circumstances, but when applied to a slip table that is binding or has stiction problems is unable to overcome static friction. This results in an inappropriate transfer function and hence an incorrect drive signal. Each of these possibilities was investigated as a possible cause and supporting data were used to systematically eliminate them as a probable cause. The rationale for their elimination as contributing factors to the event is detailed in Appendix H, Section (A12) in the Fault Tree analysis.

Controller Input is Incorrect (A13)

Another possible source for an incorrect drive signal is incorrect controller inputs to the controller. This includes calibration error, incorrect gain settings, loose accelerometer, loose cables, or a power fault. A check of test setup sheets and an inspection of signal quality indicate that none of these errors occurred. Each of these possibilities was investigated as a possible cause and supporting data were used to systematically eliminate them as a probable cause. The rationale for their elimination as contributing factors to the event is detailed in Appendix H, Section (A13) in the Fault Tree analysis.

SPACECRAFT ANOMALY (A2)

The Board reviewed all pertinent spacecraft information to determine if the spacecraft could have been a contributing factor in the sine-burst overtest. All of the accelerometer and force gage data acquired during the tests conducted on March 21 were reviewed. In addition, the Board reviewed analyses performed to calculate spacecraft modes and to demonstrate strength margins. Review of the spacecraft data provided very clear indication that the spacecraft did not contribute to the sine-burst overtest. As a result of this fact, the Board was quickly able to remove the spacecraft from the list of possible causes for the mishap.

A brief summary of each of the items on the fault tree relating to the spacecraft is provided below. The details of the data review performed for the spacecraft portion of the fault tree is provided in Appendix H, Section (A2).

Dynamic Interaction with the Test Facility (A21)

Severe dynamic interaction between the test article and test facility could result in the control system being unable to control a closed-loop test or to incorrectly calculate a transfer function for an open-loop test. Dynamic interaction with the test facility can be caused by non-linear behavior of the test article, excessive rattle at the interface to the test fixture, resonant interaction with the shaker system, or slippage between the test article and test fixture. Review of the force and acceleration data from the spacecraft tests conducted prior to the mishap shows that none of the above conditions were present. The details of this data review and the rationale for eliminating dynamic interaction with the test facility as a contributing factor is provided in Appendix H, Section (A21).

Inadequate Design Margin (A2A)

Most of the damage to the spacecraft during the sine-burst overtest can be traced to a failure of the Imager support ring. The structural margins of safety were reviewed to ensure that the spacecraft had adequate design margin to survive the intended sine-burst test level of 7.5g's and to verify that the structural failure of the support ring was consistent with strength predictions. This review showed that the spacecraft did indeed have sufficient margin to survive the intended sine-burst test level and that the failure of the interface ring is consistent with pre-test strength analysis. The details of this review and the rationale for eliminating inadequate design margin as a contributing factor is provided in Appendix H, Section (A2A).

Previous Spacecraft Damage (A22)

Acceleration and force data from the low-level sine sweeps were reviewed to determine if there was any indication of damage to the spacecraft or its interface prior to the start of the sine-burst test. If the spacecraft had been damaged during prior testing, this could result in a loss of structural integrity or could cause the spacecraft to dynamically interact with the shaker system. This type of damage could occur either to the spacecraft structure or to the interface between the spacecraft and the test fixture. A review of the sine sweep data shows no indication of damage to the spacecraft structure or the interface to the slip table. The details of this data review and the rationale for concluding that previous damage was not a contributing factor to the mishap is provided in Appendix H, Section (A22).

Not Built as Designed (A23)

The analytical prediction of structural frequencies and the determination of strength margins are based on the assumption that the spacecraft has been built as designed. Workmanship problems including assembly errors and material defects can have significant impact on the behavior of the "as-built" flight article. These types of problems can lead to unexpected structural behavior and can reduce structural margins during testing. The test data from the low-level sine sweeps were compared with analytical predictions of modes and mode shapes to determine if the spacecraft was built as designed. This comparison showed that the analytical model accurately characterized the structural behavior of the test article. This correlation activity allowed the Board to eliminate workmanship problems and material defects as contributing factors to the test mishap. The details of this data review are provided in Appendix H, Section (A23).

8. TROUBLESHOOTING SUMMARY

As previously described, we used our fault tree and the supporting data to narrow the probable cause of the test overshoot to the calculation of a poor system transfer function. The cause of this poor transfer function was hypothesized to be a combination of stiction in the shaker system and a low-amplitude self-check for run 11. The Board developed a diagnostic test plan (reference Appendix I-9) that would provide a structured method for us to evaluate the mechanical and electrical health of the system, without breaking the actual test configuration of the system, and attempt to replicate the overshoot condition of test 11. During the pre-test mechanical checks, anomalies in the slip table and granite mass were noted that supported our hypothesis of stiction in the mechanical system. At the time, there was not sufficient measurement equipment on hand to completely assess the flatness of the slip table so it was not possible to determine (later measurements showed the slip table to be flat) whether the table was tilted or warped or a combination of the two. For this reason, we did not execute the step in our plan that directed us to check the torque of the fixture bolts because were unsure if the table anomaly was related to the interaction of the fixture plate with the slip table. After all pre-test checks were completed, the system was configured for the diagnostic test. We made a best-effort attempt to configure the system as it was before run 11 on March 21. It was not possible to account for the thermal effects of the frictional drag between the slip table and the granite mass. We suspected that the frictional drag between the slip table and the granite mass during the day's testing activities of March 21 would have tended to heat the local areas of both components causing even greater interference between them due to thermal expansion. For the diagnostic test, both the slip table and granite mass were ambient temperature. This condition would possibly allow for some relaxation of the interference between the table and granite, but there was no reasonable way to account for thermal effects that we could not quantify.

When we attempted to run the self-check portion of the test it was noted that several shock transients being propagated through the system. Review of the test data from run 11, (reference Appendix I-25) showed no such transients in the system. We decided to terminate the test and obtain the relevant data from the diagnostic test run. Analysis of the time histories from our diagnostic test (reference Appendix I-10) showed several bursts that are consistent with an electrical anomaly. The "spikes" in the data show very sharp rise-times and are of considerable amplitude. These type transient events would tend to excite the resonant modes of the shaker and slip table system and would tend to lessen the stiction effects that we suspected as a contributing factor to the overtest. Since these anomalous conditions did not appear in the actual test data from run 11, we determined that the condition should be eliminated before continuation of our attempt to replicate the overshoot condition.

We developed a second test plan (reference Appendix I-11) that would allow us to isolate the cause of the electrical burst noise in the test system. After executing the steps of this test the anomaly was isolated to the DAC of the vibration control system. We replaced the unit with another unit from a sister machine and the noise was eliminated.

The system having been returned to an acceptable state, we were ready to resume the original diagnostic testing plan. We again configured the test system per the original plan and resumed the test. We were able to recreate a sine-burst (reference Appendix I-12) that had an overshoot at the –12 dB level that was outside of the acceptable tolerance range for a 0 dB test of the HESSI spacecraft. The recreated sine-burst was lower in amplitude than the one that damaged HESSI; however, some difference would be expected due to the interference of the slip table and granite mass resulting from thermal expansion as well as the non-linear effect that stiction introduces into the system. The overshoot validated our hypothesis that the HESSI mishap was the result of a combination of stiction in the shaker system and a low-amplitude self-check.

The DAC anomaly mentioned above may have been beginning to develop during the sine-burst testing that damaged the spacecraft. A review of the time history self-check data from run 11 (reference Appendix I-6a) reveals some asymmetrical amplitude characteristics during the final few seconds of the self-check. These asymmetrical bursts could be indicative of an impending DAC failure or they could be RF interference. It is not possible to quantify their cause and it is not believed that they contributed to the incident in any way. Their occurrence is noted here in the interest of completeness.

9. FINDING, ROOT CAUSE, CONTRIBUTING FACTORS, OBSERVATIONS, AND RECOMMENDATIONS

A finding is a conclusion based on facts established during the investigation by the investigating authority. The root cause of a failure is the mechanism that directly caused the mishap. Contributing factors are events or conditions that if identified, could have been used to prevent the mishap. Observations are items that did not directly affect the mishap but could potentially cause a mishap or subject the flight hardware to undue risk. Recommendations are included for each contributing factor and observation.

Finding: The HESSI spacecraft was subjected to a significant sine-burst overtest condition that resulted in damage to the spacecraft. Stiction (static friction) between the granite reaction mass and the slip plate of the shaker-system combined with a self-check performed at very low force input levels resulted in the calculation of an inappropriate drive signal. The resulting pulse was significantly higher in amplitude than expected, thus yielding the subject overtest.

Root Cause: Stiction caused by misalignment of the shaker and slip table was the root cause of this mishap.

Contributing Factors:

1. Misalignment caused the slip table to exhibit non-linear behavior in that it would bind at low levels of force input.

   Recommendation: Develop metrics for routinely assessing the mechanical "health" of the shaker and slip table systems. This would include mechanical measurements as well as periodic test runs of the system under defined input levels. This data could be compared to the same data from previous measurements to identify any changes to the test setup that might cause an improper test condition.

2. The test personnel did not have knowledge that data was available to assess the quality of the transfer function calculated from the self-check prior to initiating the sine-burst test. Post-test review of the transfer function used to generate the shaker drive signal for the test and examination of the drive voltage indicated that the test setup was not operating as expected and that an overtest could occur.

   Recommendation: Additional steps should be added to the test procedure for sine-burst and shock testing to review the transfer function and calculated drive voltage after the completion of the self-check and prior to initiating the sine-burst test. While it is not possible to set absolute standards for the transfer function and drive voltage values, as a minimum this data should be reviewed to ensure that the results are consistent with similar data from previous tests and/or a validation test for sine-burst and shock.

3. Another contributing factor to the mishap was the lack of a facility validation test using the sine-burst on the shaker table before the spacecraft was mounted. It is common practice to do a facility checkout with a similar type of test before mounting a piece of critical hardware.

Recommendation: Prior to arrival of the test article, all proposed tests should be simulated using levels which replicate as closely as possible the expected test input conditions. This serves two purposes, 1) to uncover any problems with test equipment or test requirements prior to the start of testing and 2) to provide a baseline for behavior of the system prior to start of testing with the test article. This baseline data can then be used during testing to assess whether any changes have occurred that may adversely affect subsequent tests. The validation test should be done in such a way as to closely replicate actual test conditions. Control software setup, amplifier gains, control charge amplifier settings, self-check amplitude, test hardware gravity loading and any unique conditions that affect the response of the system should all be representative of the actual test conditions.

4. One of the contributing factors to the mishap was a mechanical anomaly that occurred in the exciter system. The shaker, a Ling A-249, appears to have shifted in its support cradle after being coupled to the slip table in preparation for this test. The shift resulted in a misalignment that brought one area of the slip plate into contact with the granite reaction mass creating a much larger frictional drag than normal.

   Recommendation: Refurbish or replace the Ling Model A-249 shaker.

5. Another contributing factor to the mishap was the low amplitude of the self-check used for the test. If a higher amplitude self-check had been used, the control software would have more closely approximated the system transfer function. A higher self-check would have lessened the effect of the slip plate to granite stiction and would have given a more accurate transfer function.

   Recommendation: Perform self-checks at appropriate levels such that the transfer function of the system will be representative for the force required to perform the test.

Observations:

1. The sine-burst test setup does not currently include independent over-test protection methods, such as a trip circuit based upon acceleration or displacement limits. By contrast, the random vibration test includes redundant control accelerometers, acceleration trip circuits, and a third monitor accelerometer. Adding these trip systems to a sine-burst test is not an easy matter, because these tests often call for sizeable velocities or accelerations that cannot always be safely terminated by simply shutting down the power amplifier. The board members had several discussions on the viability of hardware/software strategies that might provide safe or controlled shutdowns. The wide-ranging discussions even included new methods for implementing a "closed-loop" sine-burst test. While none of these techniques appeared ready for immediate implementation, many seemed worthy of additional study and even testing. Present day hardware has the capacity to prevent repeated cycles of over-tests, but may not be fast enough to prevent the first excursion.

   Recommendation: JPL shall implement overtest protection methods for sine-burst testing. Protection methods for this type of testing have been satisfactorily implemented at other NASA test facilities.

2. The HESSI project was not fully aware of the risks associated with the sine-burst test that uses a computer generated open loop drive signal. The program risks are

magnified when this test is performed late in the test flow at the “all-up” spacecraft level. Many of the UCB personnel indicated that they had not previously been involved with a sine-burst test or had been involved with sine-burst testing at lower levels of assembly. If the HESSI project had fully appreciated these risks, they might have selected a different verification method for strength qualification of the spacecraft. However, the project’s tight schedule may still have discouraged selecting a different strength verification approach.

In more traditional projects, the flight structure qualification tests are performed with mass simulators. This practice reduces the risk to flight hardware that can be caused by structural failures. In addition to sine-burst testing, projects can elect to perform structural qualification testing using either static pull or centrifuge tests. These tests generate safer and easier to control static loads. The sine-burst test is attractive because it can be conducted at the same time as other vibration tests, saving both time and money. However, performing strength testing at the “all-up” spacecraft level can subject flight hardware to an unacceptable risk of damage.

Recommendation: Projects electing to perform sine-burst testing at the “all-up” spacecraft level should be made aware of the risks associated with this approach. Strength qualification, especially using the sine-burst test method, should be performed at the lowest level of assembly as possible to eliminate the risk of damaging sensitive flight components. The NASA community should be encouraged to develop safer methods and more comprehensive procedures for this test because it is a very quick and thorough qualification method. However, the decision to perform strength testing at the “all-up” spacecraft level should be carefully weighed against the risk of damaging flight hardware.

3. The sine-burst frequency was not specified in the test plan. This frequency is a parameter that is selected to avoid undesired dynamic response in the spacecraft and the test facility. As indicated in the test plan, the frequency was selected after reviewing the sine sweep test data. When a sine-burst frequency is not specified prior to the test, ability to perform a pre-test checkout of the test facility is hindered. In addition, decisions about the test frequency must be made quickly during the test process. The routine facility checkouts at this facility, however, included only a low-level sine sweep. There is no evidence to indicate that inclusion of the sine-burst frequency in the UCB test plan would have mitigated the occurrence of this incident.

   Recommendation: A sine-burst frequency should be included in the test plan. This will support the conduction of an accurate validation test. This frequency selection should be made using the best structural analysis model available at the time. While the behavior of the actual structure may differ from the analytical model, the differences should not be significant enough to negate the validity any pre-test simulation of the sine-burst test by the test facility. In addition, selecting the sine-burst frequency in advance of the test allows for more time to weigh all factors in selecting the appropriate test frequency.

4. The following three observations address concerns with the JPL test procedures and their execution:

   (a) The test procedure did have a step (Appendix C-3, Environmental Dynamics Test Laboratory Test Procedure for the Protoflight Sine-burst Testing of HESSI Spacecraft, step 14) that called for Quality Assurance to verify that all critical steps had been completed prior to conduct of the test, however, this step was not stamped or initialed in the "as run" test procedure. It is currently JPL practice to allow the Project Representative to determine if this check is required. Although the investigation did not find any errors in the performance of the critical steps for this test, the practice of permitting the omission of this critical check is questionable. Historically, simple human error is often the primary or a contributing factor in test anomalies. The expense of performing this independent check is minimal, especially when compared with the potential consequences to high value flight hardware of an inadvertent human error in test setup.

   Recommendation: JPL should reassess their policy that permits the omission of critical checks that are intended to reduce or preclude the potential of single point errors that could damage or destroy high value or critical hardware.

   (b) The written test procedure for the HESSI sine-burst test did not include the critical steps of turning on the low pressure and high pressure oil pumps. It should be noted that everyone involved in this test is quite certain that the pumps were turned on and as a result did not contribute to the test anomaly.

   Recommendation: In order to help avoid any future oversight that could lead to running the table without the necessary lubrication, these steps should be added to the procedures critical step list. In addition, the incorporation of system interlocks that would prevent running the table without the pumps turned on should be considered.

   (c) The written procedures generally did not have full coverage of the pretest setup and post-test teardown phases of the process. For every test of flight hardware, there should be a procedure that can be used to repeat the exact steps taken to cover pretest and post-test activities.

   Recommendation: Expand the written procedures to fully cover the pretest and post-test phases for flight hardware testing. This should include all electrical, fluid and data hook-ups. Validation that the mate or torque, for example, was successful should also be included. Post-test procedures should be written to undo the pretest activities to return the flight article to the same condition as pretest. Any exceptions should be fully documented and addressed. In this way, the flight spacecraft owner will have full information on everything that was done during the entire test campaign.

5. The flight hardware, while in the JPL test facility, was not consistently protected against inadvertent mishaps to the same level as JPL in-house projects. Specific flight hardware support equipment, tools and other associated gear was not separated from the general facility equipment. Test support equipment that interfaced with the flight hardware was not clearly identified and protected. In addition, critical hardware lifts

and moves were not fully planned beforehand to safeguard the hardware. For example, before the damaged spacecraft was lifted from the test fixture the lifting crew was made aware of the absence of shackle-pin spacers in one part of the JPL-provided rigging. Spacers, required to center the load-path on a shackle-pin, were missing causing the shackle to be in a side-loaded condition. The roles and responsibilities between the test facility and spacecraft organizations, although generally defined, were not explicit in some areas, such as hardware lifts and moves.

Recommendations: JPL should assure their equipment is being used in a safe manner and all flight hardware is adequately protected. For example, have specific areas designated for flight hardware, flight ground support equipment (GSE) and tools. The flight and non-flight hardware, such as mechanical fasteners, should be clearly separated so that non-flight substitutions on the flight hardware will not occur. All tools used on the spacecraft should be noted in a log. There have been instances on other Projects, where tools have been left by mistake and caused damage in flight. Test cabling that interfaces with flight hardware should be treated with the same care as the flight hardware. The interface connectors should be protected by covers or bagged for protection from debris. Cabling should be protected from inadvertent damage. This can be done, for example, by using hard covers or raising the cabling off of the floor.

Transfer paths for movement of flight spacecraft should be cleared, marked and controlled. A thorough premove or prelift walkdown should be performed. All handling equipment, such as slings and move fixtures, should have in-date certifications and be cataloged with a listing available at the test site. These certifications should include items such as proof loading and electrical checks. The Quality organization should inspect these records and overall planning paper. Critical handling steps should be well documented and personnel should be trained and certified. In the case of the HESSI spacecraft, the HESSI developer, UCB, was responsible for the critical moves and lifts. In this case, the UCB personnel should be fully certified in all aspects of operations of the JPL test facility equipment that they are to operate. The test facility personnel should provide very thorough training and certify specific personnel that have passed the training. Although UCB has the responsibility for the lifting, the JPL personnel have the ultimate responsibility to make sure that their equipment is being used in a safe manner and that the test article is protected.

6. Problem Failure Reports (PFRs) from previous test anomalies did not include complete equipment lists of the test system configuration at the time of the anomalies. Over time, components, especially electronics, are substituted or replaced, making it difficult to determine if any specific component of the test system may be common to a number of anomalies. In addition to their value in anomaly investigations, complete equipment lists provide valuable information in troubleshooting, maintenance and refurbishment activities.

   Recommendation: The practice of documenting the test system configuration, and including this information in PFRs when anomalies occur, should be considered.

10. LESSONS LEARNED

Based on the factors associated with the mishap, the following lessons learned have been identified:

- Test facilities must be maintained such that the test equipment is in good working order. Metrics must be developed and tracked that assess the mechanical health of the systems.
- "Canned" tests should be developed and periodically utilized to provide a trended database for the test systems' response. Any deviations in the system response should be investigated.
- Critical control system response data such as the transfer function or inverse transfer functions, and calculated drive voltage must be evaluated real-time during testing to ensure that they are reasonable and do not indicate system maladies.
- Facility validation test should be done for each planned test series that are representative of the actual test conditions before flight or critical hardware is mounted.
- Self-checks should be done that provide a representative response for the forcing range of the planned test. For higher force shock tests, shaker systems and test fixtures often do not respond in a linear fashion. It is also foolhardy to assume that test facilities are always in perfect working order.
- All test requirements should be defined in the test plan for a particular test. The test operators must have adequate data to enable complete verification testing before testing critical hardware.